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CSMA/RN - A Universal Protocol for Gigabit Networks

A White Paper

by

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1.0 Introduction

Networks must provide intelligent access for nodes to share the communications resources. During the last eight years, more than sixty different media access protocols for networks operating in the range of 50 to 5000 Mbps have been reported[1]. At 100 Mbps and above, most local area [LAN] and metropolitan area networks [MAN] use optical media because of the signal attenuation advantage and the higher data rate capability. Because of the inability to construct low loss taps other than star couplers, fiber optics systems are usually point-to-point.

In the range of 100 Mbps - 1Gbps, the demand access class of protocols have been studied extensively. Many use some form of slot or reservation system and many the concept of "attempt and defer" to determine the presence or absence of incoming information. Local sensing of the existence of information is used in slot, train and reservation systems such as Cambridge Ring [2], Expressnet and Fastnet [3], and DQDB (formerly QPSX) [4]. In slotted systems, long messages must be broken into slot size proportions contributing to wasted network capacity, since the slot size selected is always a compromise over the wide range of integrated (voice, video and data) traffic that high data rate networks must carry. Also, recent studies indicate that reservation systems have fairness difficulties when servicing nodes at the ends of the bus under high load conditions[5]. Other demand access systems may use a token, like FDDI, but waiting for the token to rotate can cause slow access especially in longer and higher data rate rings. In addition, most demand access systems use a master controller mechanism, like in FDDI II, for handling synchronous traffic [6, 18].

The random access class of protocols like shared channel systems (Ethernet), also use the concept of "attempt and defer" in the form of carrier sensing to alleviate the damaging effects of collisions. In CSMA/CD, the sensing of interference is on a global basis. However, as bandwidth increases, a message spans a smaller portion of the global bus length so network collisions can reduce throughput significantly, especially at higher load [7]. This, coupled with the fact that optical broadcast systems have a difficult time building effective low loss taps, makes global sensing impractical for high speed networks.

Some systems have used a delay line [8] or a buffer, like the register-insertion system [9, 10], for alleviating the corruption of data because of simultaneous access. The tree LAN system [8] uses "attempt and defer", while the register-insertion system uses "attempt and defer" or "attempt and hold" under full or empty buffer conditions, respectively. Finally, a hybrid system [11] uses "attempt and abort" under some conditions but reverts to a master controller at high loads when aborting begins to waste needed network capacity.

All systems discussed above have one aspect in common, they examine activity on the network either locally or globally and react in an "attempt & whatever" mechanism. Of the "attempt + " mechanisms discussed, one is obviously missing; that is "attempt & truncate". As noted above, the amount of space occupied by a packet decreases as network rate increases. For example, at 100 Mbps, a 2K bit packet occupies a space of approximately 4 km along the network ring; at 1 Gbps, this space is reduced to 0.4 km. Thus, a 1 Gbps, 10 km network can potentially have 25 separate 2K bit packets simultaneously in existence over its span.[1] Thus, as bit capacity of the network increases with data rate, it would seem reasonable that, at least for some load conditions, truncating a message when it is about to interfere with a message on the system and resuming it later when free space is available would be a reasonable access protocol to consider.

"Attempt and truncate" has been studied in a ring configuration called the Carrier Sensed Multiple Access Ring Network (CSMA/RN). In this paper, we will describe the system features of CSMA/RN including a discussion of the node operations for inserting and removing messages and for handling integrated traffic. We will then discuss the performance and operational features based on analytical and simulation studies which indicate that CSMA/RN is a useful and adaptable protocol over a wide range of network conditions. Finally, we will outline the research and development activities necessary to demonstrate and realize the potential of CSMA/RN as a universal, gigabit network protocol.

2.0 Carrier Sensing and Control in Ring Networks

Local carrier sensing and collision avoidance is used in all "attempt & whatever" mechanizations. It has been implemented using a delay line for a tree LAN optical network operating in the Gbps range[8]. This network has a number of receiving links and a transmitting link at the node points of the tree. Each receiving link can have an incoming signal but only one outgoing signal can be propagated. The key to sensing selection is based on a delay line that gives the selection switch advanced warning of the incoming signal and hence, a chance to exercise intelligence to select a single receiving line and avoid a collision before the signals arrives. This same form of advanced information detection and control is the key to the CSMA/RN operation.

2.1 Basic Operation

Figure 1 illustrates the characteristics of a node in the carrier sensed ring network. The incoming signal is split into two streams, one through a delay line or buffer. Note, the delay can be relatively short if high speed logic is used in the controller system. For example, a 100 bit delay at 1 Gbps is approximately a 20 meter piece of fiber and causes a 100 nanosecond delay. The node controller, based upon information accumulated, is required to make a number of decisions. First, it must detect the presence of incoming data; if its exists, the node must always propagate incoming information as the outgoing signal to the next node on the ring because it would be impossible to recreate the packet unless a much larger storage system is provided [9]. If no incoming packet exists, the node is free to place its own data on the ring if its queue is not empty. However, during the time this latter data is being transmitted, if an incoming packet arrives, then the node, within the time limits dictated by its delay size, must discontinue its transmission and handle the incoming packet. When truncating a packet, the node can place a terminator block at

[1] Some demand access systems realize this sharing of physical network space by having multiple trains or slots distributed over the network length.

the end to assist the receiving node with re-accumulating a fractured message.

Packets are tested at each node to determine if the incoming packet is destined for this node and should be copied to its receiving data buffer (not shown in Figure 1). Since address decisions are required by the controller, packets are nominally removed at the destination, since, as discussed in Section 4, destination removal increases network capacity significantly. As a protection against packets circulating continuously in case of node failure or address errors, packets are removed by the source after one or more rotations by comparing addresses against an established list.

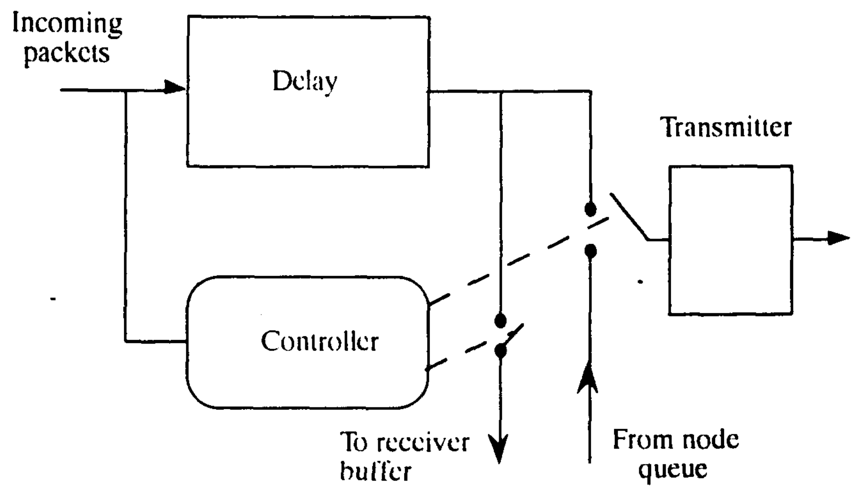

Figure 1 CSMA/RN Access Controller Logic

2.2 Synchronous Traffic Operation and Guaranteed Access

A most difficult problem for random access protocol systems occurs when integrated traffic and guaranteed access are required. In CSMA/RN, we have solved both problems by the use of a circulating packet reservation (CRP) system[2] which is similar to the concept we developed in DRAMA [12].

In the reservation system, a special small packet, about 100 bits, circulates continuously around the ring for nodes having synchronous traffic or requiring guaranteed access. The synchronous traffic is attached to this packet. To set up a call, the node informs the rest of the network of the bandwidth needed and the expected inter-arrival time of messages. After checking that this additional call does not require any parameter changes to the protocol, the node proceeds to send messages as follows. On the cycle prior to the node's need to submit synchronous traffic, the node through the packet requests that a block of space following the packet be freed for its use on the next cycle. The node is free to set this indicator whenever it has synchronous traffic and the reservation packages is *free*. When the nodes makes the reservation, it also sets the flag to *busy*; after a complete cycle the node changes the flag to *free* and sends its synchronous message(s) in the free space behind the CRP. In most cases, the capacity reduction due to a circulating reservation packet is very small so that the net can have one or more packets depending node count and ring length. The separation of circulating reservation packets will

[2]We have not considered implementing an isochronous traffic system as this would requrire a 125 μsec. cyclic control. Our intention is not to compete with the telephone network to handle virtual circuits by framed time-division multiplexing but to integrate periodic traffic into a multi-area, gigabit data network.

limit the size of regular data packets so the number of reservation packets on the system should be regulated. The block size requested by a circulating packet depends upon the synchronous traffic bandwidth required and the inter-arrival time of the useable circulating packets.

As the CRP request circulates around the network, the space is freed as the packets arrive at their designated destination. However, this space can be used further if the destination node or any subsequent node has a message for any node between and up to the node controlling the circulating packet. In addition, the node controlling the circulating packet does not need to request space to a greater extent than needed. For example, a telephone call which goes into the non-talk phase, no reserved space or only a minimal block would be required for that cycle. Hence, synchronous data block space is used only as needed and unused space does not need to be recovered. As a result, the CRP system and handling of synchronous traffic should cause minimal impact on the CSMA/RN network system.

Guaranteed access works in conjunction with the CRP system. Access is guaranteed one revolution after receipt of the free circulating packet. To guarantee that nodes have access to free circulating packets requires that a node cannot use a circulating packet on a number of successive revolutions. By passing it packets on, every node is will get to see a free circulating packet within a fixed number of ring revolutions. Access time depends upon the conditions established for network operations based upon the number of nodes, the number of circulating reservation packets and the ring length. If the network can not guarantee the access time specified with the one reservation packet, it can introduce another one into the ring. This will impose a new limit on the maximum message length but will lower the current worst case access time by half after the same synchronous traffic is redistributed equally. Alternatively, if circulating reservation packets are not being used, they can be eliminated from the system if access times are acceptable.

2.3 Fairness

Fairness in any basic CSMA system can be a problem since access is based upon statistical probability. Fairness problems are most likely to occur when a node up stream has a long or a lot of messages to send and fills all the packets, or a node down stream is sent many messages by a nodes up stream. For example, when we have non-uniform load such as a node being a file server or a bridge which both sends and receives more than other nodes, actual starvation at either side of this node can occur.

To solve the fairness problem, we propose to use a scheme first investigated for DRAMA [12]. In DRAMA, a multichannel protocol, a small channel was set aside for transmitting global information which among other things transmitted network averages of all channels to all nodes. It is more efficient to do so than to have each node monitor every channel since at any time a node participated only on a few channels. Nodes use this information to adjust their bandwidth usage so that every node would experience approximately the same access delay. That is, nodes with lots of information to send obtained lots of bandwidth and those with little got little bandwidth assigned. The algorithm was totally distributed and was able to totally reallocate bandwidth upon strong disturbances within 30 msec.

CSMA/RN is not a multichannel protocol, but, analogous to the global communications channel in DRAMA, we can reserve a small, 100 bit, circulating fairness control message in CSMA/RN. The information in this fairness message is the current network throughput averaged over all nodes and the average wait time per message, call it *nm*. That is, it is the average of all nodes perception of the traffic on the network - remember that, in general, no node will see the same amount of traffic pass by because messages are taken off at the destination.

To keep *ntn* current each node keeps two copies - one from the last cycle and one from the current cycle. When the fairness control message comes around, the value is replaced by the one the node has calculated during the last cycle. The value which was taken off is used to calculate the value for the next cycle as follows:

$$ntn = ntn - last/n + current/n$$

where n is the number of active nodes. If a node finds that its current throughput is more than the $p\%$ of global-node-throughput, and its wait-time per message is less than $q\%$ of the network wait-time per message, the node is forced to wait for x Kbits hole in that ring cycle. With this control, a hyperactive node is forced to abstain from sending messages on the ring and giving other nodes a chance to send their messages.

3.0 Performance of CSMA/RN

Both analytical and simulation performance studies of CSMA/RN have been conducted. The analysis results show that a simple queuing theory model displays excellent correlation with the simulation results. The model assumes each node to be statistically independent with its message service time a function of the probability of the arrival of a free message block based upon the network load. Under these conditions, the queuing theory model is basically M/G/1 so that the wait time for messages in the queue can be found directly from the Pollaczek-Kintchine analysis [13]. Once the message has been serviced and is placed on the network, the travel time from source to destination is fixed by the network propagation speed. Hence, the response time for a network, which is the sum of the wait, service and travel times, is easily obtained.

The major factor in obtaining accurate analytical results for the above model is a good estimate of the arrival of free message blocks so that service time results are accurate. Two models were developed which give probability of a free packet based upon load factor. One ignores and the other models the effect of packet size based upon packet fracture results obtained from the simulator. Interestingly, the former model was found to provide better results because, although packets may fracture, the smaller packets arrive more frequently, so the net result is that the service time is approximately the same, independent of whether many small or a few large empty blocks arrive.

The simulation was built to study the parametric aspects of CSMA/RN which are not modelled in the analysis. During the simulation, runs were made to examine the statistical properties of the results so that run-times would provide accurate data. General conditions for the initial simulator runs include:

(1) packets were removed at the destination and the empty space used by the node to send queued messages;
(2) additional header bits required because of packet fracture were not added to the message,
(3) nodes are uniformly spaced around the ring;
(4) all message arrivals are uniformly distributed among the nodes;
(5) all message destination addresses are uniformly distribute among the nodes other than the source node; and

(6) all messages are fixed length.
Additional runs were made where conditions 2) and/or 6) have been removed.

3.1 General CSMA/RN Performance[3]

The simulation results for a 10km, 10 node ring, Figures 2 and 3, indicate that under nominal conditions CSMA/RN provides excellent performance as an access protocol. First, access or wait time approaches zero at no load and remains relatively flat until the load approaches 140% of the network load. As load increases, wait time, which is dependent upon service time, becomes unstable, nominally at loads > 200%. Service time remains close to the minimal, no load service time throughout most of the load range; it remains within a factor of 2 for load levels up to 120% network load and with a factor of 4 for loads up to 200%. Finally, since travel time for a message on the ring is fixed by the media propagation speed, the total response time in MAN and larger LAN networks is mainly dependent upon the source to destination length. In any case, the CSMA/RN access protocol does not slow the travel time, so that a message, once on the network will move as quickly as possible to the destination.

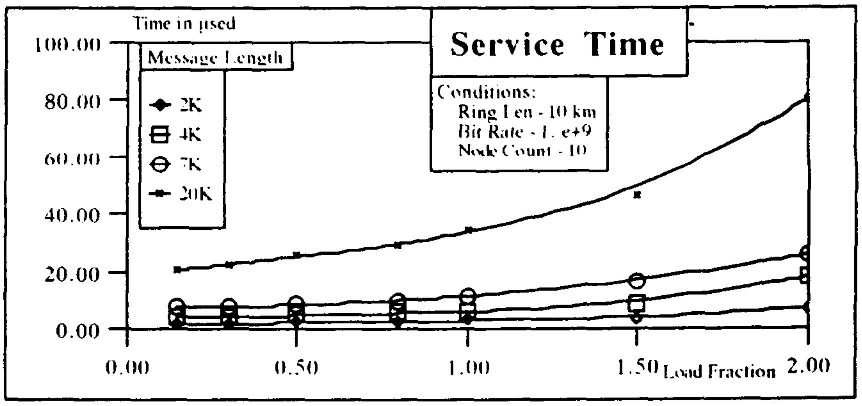

Figure 2 Service Time for CSMA/RN Access Protocol

As mentioned previously, the performance of the CSMA/RN is improved by using destination removal of messages. This is immediately apparent from Figures 2 and 3 ---the 1Gbps network is capable of handling up to 1.75 Gbps (175% load factor) without saturating, because, on an average, messages travel only half way around the ring. Thus, load performance for CSMA/RN and other destination removal networks systems, like register-insertion [9, 10], can double the basic net capacity.

In the initial simulator studies of CSMA/RN, runs were made varying a number of conditions. Node counts were varied from 10 - 200 nodes, ring lengths from 2km - 10000 km, and message lengths from 2K - 2 Mbits. In all cases, CSMA/RN performance was considered to be excellent and to correlate closely to the expected results from the analytical studies up to the maximum load factor of 200% (2 Gbps).

Additional features were examined using the simulator system. Message fractures were determined for all runs. In most cases, mean message fracture ratio was below 2.5 for all conditions above when load factors was less than 150% and usually below 4 for loads up to 200%. The maximum mean message fracture was noted for high node counts (short inter-node

[3] Details on CSMA performance studies can be found in [15]

distances of 0.25km) where mean message fracture was 7 at 200%. Simulator runs made with overhead added for message fracture (condition 2 above removed) showed a small increase in wait, service and response times and message fractures for load conditions up to 175% .

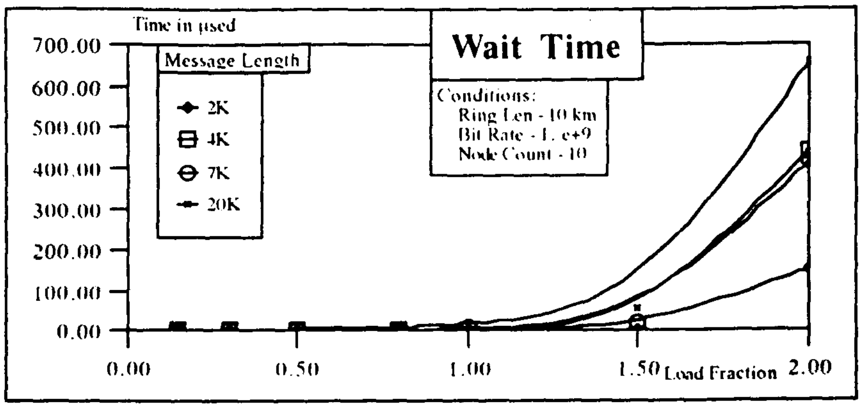

Figure 3 Wait Time in Queue for CSMA/RN Access Protocol

Simulator runs were made to test throughput at overload conditions. At 250% input load, the network delivered over 190% of capacity. Simulator runs were made at lower network data rates to determine whether CSMA/RN is an effective protocol in the megabit range. The results showed that protocol performance was good and as predicted by the analytical model at data rates to 100 Mbps. We anticipate that this limit can be decreased for longer length networks. Additional simulator runs have been conducted with random message sizes ranging from 2000 - 6000 bits. The results show no significant increase in service time or packet fracture but some increase in wait times at the higher load fractions, as predicted by the Pollaczek-Kintchine formulation of the analytical model, due to the increase variance in the service time.

Finally, a scaling factor suggested by the simulator model has been shown to be accurate in predicting CSMA/RN performance for wide area ring networks. In scaling, the ratio of network length to message length is fixed and the number of nodes remains constant. Simulator runs were made for 4 conditions up to 10000 km and 2 Mbit message lengths and compared to performance based upon scaling up from 10 km and 2 Kbits. Comparisons showed results were almost identical. Thus, one can predict performance of WANs to be the same as those from scaled LANs with the exception that travel time once the message is on the network will be greater. Using these scaling conditions, CSMA/RN is shown to provide an excellent access protocol for a National Research and Education Network[14].

3.2 Synchronous Traffic Performance

Simulation runs have been made with the above model to test the impact of the circulating reservation system's circulating packets on the networks asynchronous performance. As noted previously, the CRPs will limit the maximum size that a normal packet can have when the CRPs are space uniformly along the network. Tests were made on a 10 km, 10 node ring with 4 Kbit messages. Each circulating packet was 100 bits long. Each circulating packet will reduce the network capacity by 0.2%. More important, each circulating packet will recur at a node every 50 μsec. Tests were run with 1, 2, and 5 circulating packets. Five circulating packets limit the maximum size of message blocks to 10 Kbits and CRP inter-arrival times to 10 μsec.

The results of the runs showed that the maximum impact of the the circulating packets was to increase the message fracture, especially at low loads. Here, 5 CRPs produced a fracture ratio of 1.9 packets per message at 30% load, for 1 CRP, it was 1.21 and with no CRPs the fracture was 1.15. The service time at low loads was also increased by not nearly as significantly. At high loads, the circulating packets did not have as great an effect since packets already tend to be quite fractured and the interruptions by the circulating packets made minimal additions. The results indicate that, for nominal circulating packet inter-arrival times of 50 - 200 μsec., CRPs should not nave a significant effect on the data traffic that the network is carrying. In addition, we have analyzed a group of synchronous traffic scenarios. In all cases, the maximum guaranteed access was less than 1 msec. and in rare cases the maximum message length was reduced to 10 Kbits.

3.3 Fairness Tests[4]

The CSMA/RN simulator presently available does not model non uniform and highly variable traffic from a node. However, some examples of the fairness problem were observed and initial tests were made on the fairness control model to determine its effectiveness. At 200% load four nodes suffer severe starvation, sending from 166% to 176% and at 225% load nodes, twelve nodes had between 180%-190% and five nodes had below 180% throughput. Since the results are based upon random distribution, conditions will vary over different runs and over different intervals in a run.

We have run experiments with a network in which a specific node is starving for a certain period of time under a nominal load condition of 250%. During a 30 msec. duration of starvation, the node's waiting time increases significantly from 425 msec. to 1038 msec. In this specific case, the node is unable to sent its messages even at expense of higher wait-times per message, mainly due to the fact that the node does not receive many messages and hence, does not see empty packets on the ring. In such an overloaded net the bus will be practically busy all along its length, so a node gets 75% to 98% chances of sending from being able to take off messages addressed to it and thereby creating a hole to send its message. We have implemented the fairness control scheme described in section 2.4 with p and q being 20% each. Now the same node as in previous case starves only for 20 msec. The wait-time is still high because of the overload situation being experimented. Most significant, however, the node is able to send 86 messages in a 1 msec. period with the fairness control enforced; without fairness control the node only sent 53 messages in the identical period. This test indicates that the fairness control system we have adapted from DRAMA has the potential of solving node starvation in the CSMA/RN system.

3.4 Comparison to Metropolitan Networks

CSMA/RN, by its basic operating premise, is a protocol which works better at higher speed and longer length networks. Although 100 Mbps is at the low end of effectiveness for CSMA/RN, we feel it useful to give some calibration of performance by comparing it with well known high-speed protocols such as FDDI and DQDB. We have already shown earlier that CSMA/RN

[4]Further results on fairness can be found in [5]

exhibits the very low wait time at lower loads due to the nature of CSMA-type protocols and that the instability point is well beyond 150% offered load. In Figure 4, we have plotted the wait times of FDDI, DQDB, and various forms of CSMA/RN for the conditions of a 50 km, 50 node network with uniformly distributed offered load. The legend indicates the basic data rate that a particular versions can handle; that is, *CSMA 0.1* means that a node can send up to 100 Mbps. Figure 4 shows that *CSMA 0.1* outperforms FDDI significantly although circuit speed is comparable. *CSMA 0.15* ,which has the same circuit speed as DQDB but one bus as compared to DQDB's two buses, performs equal to DQDB at high loads and better at lower loads. Beyond *CSMA 0.15*, all versions are better than either FDDI or DQDB.

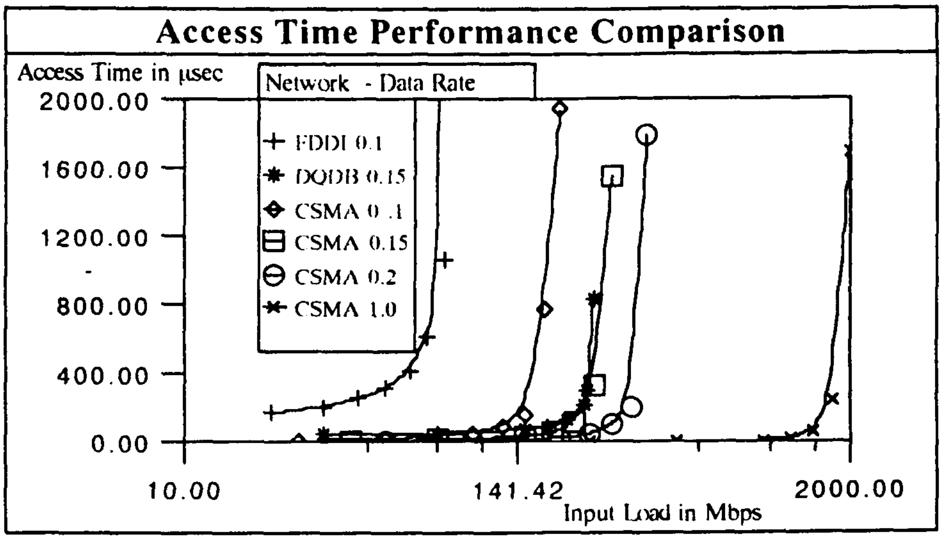

Figure 4 Performance Comparison between High Data Rate Access Protocols

4.0 CSMA/RN Operational System

The analytical and simulation studies indicate that CSMA/RN is a media access protocol which can operate effectively over a wide range of network conditions. In the following we, will briefly discuss the operational aspect of the access controller. The access controller must perform it operations rapidly; for a 1 Gbps system with a 100 bit delay buffer, the total operational time is 100 nanosec. A suggested packet frame is shown in Figure 5.

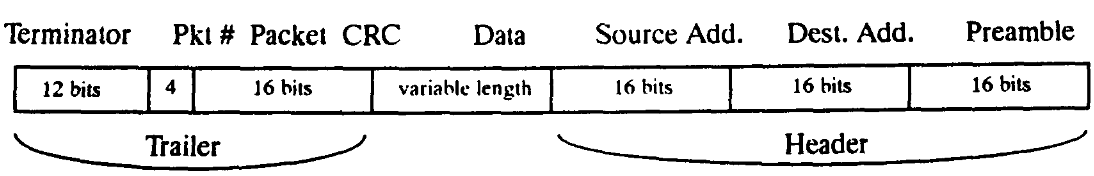

Figure 5 Packet Frame Structure

It is assumed that the network would use some form of encoding, possibly 5:4 bit encoding similar to that used in FDDI systems. If a node is transmitting, then after the first 4 bits of the preamble or 4 nanosec, it is alerted that an incoming message is arriving. The preamble is a unique 16 bit code. After the 16 bit preamble, the two 16 bit addresses must be decoded. After 48 nanosec., the node can decide whether an outgoing packet must be truncated. If the outgoing packet is to be terminated the access controller has 20 nanosec. to make the decision and switch to place the trailing information into the packet. It is assumed that the packet count and terminator block can be prepared before hand, since, in anticipation of a possible switch, after 4 nanosec., the packet CRC system is able to select the last bits in the message buffer and complete its CRC block calculations. Hence, the access controller system has 64 nanosec. to finish the CRC calculation in anticipation that it may be needed.

The access controller must contain additional logic related to the circulating packet reservation and firness control systems. It must remember whether the last reservation packet was set, maintain a count of the free space requested and the location of the requesting source so that it can decide whether to free or use the space behind the CRP. For fairness control, it must be ready to remove and re-insert information in the fairness control packet. However, the logic for these actios can be made in a somewhat more leisurely time frame.

CSMA/RN can be implemented as the low level access protocol interfacing with the physical transport media of the network. However, equally important it could be implemented above the present or future frame and channel structure of a telephone carrier system. The basic synchronous mode transfer (STM) frame/channel structure prescribes that channels of fixed length are imbedded within a frame. Asynchronous mode transfer (ATM) structures are variable in length but provide unique header and trailer terminators [16]. Each block or channel carries a call which at the receiving end is directed to a transmitter system which imbeds the information into a new channel in a new frame for travel to the next receiver. The call information continues this process from source to termination in what is known as a virtual circuit from the source to the destination phone. STM frames recur every 125 μsec., the isochronous repetition rate, and carry 8 bits for a data rate of 64 Kbps.

For virtual CSMA/RN, we propose to reserve channels within a frame. Channels are allocated to form a virtual circuit from node to node in such a manner that a virtual ring is formed. At the receiving node, those channels allotted to the ring are examined as they arrive and if empty up to the delay time window, the node is free to start or continue inserting its queued messages. When an incoming message arrives it is checked for destination and deleted or forwarded as required. Synchronous traffic would use the circulating reservation packet system described above and isochronous traffic, the underlying frame/channel system. From the CSMA/RN standpoint, the only difference between the physical and virtual implementation is that, in the latter, there will be channels occupied by other messages which will bypass the controller logic completely. The additional problem created by ATM framing would be that the system would have to identify the frame as belonging to the ring. The advantage is that blocks can be considerably longer than the basic 8 bit channel so that virtual circuit operations may be smoother. It may be desirable to implement circulating frames within the ATM system thereby maintaining a reasonably fixed bandwidth for the network. This condpet is similar to FDDI II which embeds data traffic in unused channels in its frame structure [18].

Virtual CSMA/RN can be viewed to have a number of significant advantages. From an implementation standpoint it should be able to use logic similar to that now being used in the telephone switching system. Unlike physical CSMA/RN, the arrivals may have delays between distinct channels so the node logic may be better implemented with a delay buffer as opposed to delay line. In addition, it would be anticipated that the ring network could add or release channels as its load changed thereby keeping the network resources used to a minimum based upon good performance. Such a system could potentially provide a constant, uniform network service over a wide range of network and load conditions. Finally, using the virtual circuit ring system, multiple rings could be established adding to over all reliability and to the possibility that for time-critical transmissions travel time could be optimized.

5.0 Research Issues for CSMA/RN

Clearly, CSMA/RN is beyond the conceptual state. To date, studies have demonstrated its capabilities, including:

1) virtually immediate access and minimal message fracture for loads up to 150% of capacity;
2) ability to handle widely varying message sizes;
3) up to 175% of rated network capacity without overload (1.75 Gbps traffic for a 1 Gbps network data rate);
4) synchronous traffic with little overhead, <1%, with no global master controller and automatic recovery of unused synchronous traffic bandwidth;
5) guaranteed maximum access time < 1 msec.; and
6) capability to span distances from 2 km - 10,000 km and wide range of node counts.

Hence, CSMA/RN approaches a universal media access protocol for gigabit networks.

There remain many questions and research issues which must be investigated in order to fully understand and use this media access protocol to implement gigabit networking. First, better analytical and simulator models of CSMA/RN performance are required in order to fully document its capabilities under the wide range of conditions existing in high data rate networks. Loads must include both synchronous and asynchronous, non-uniform traffic like that experienced at servers, gateways, and bursts to and from supercomputers and over longer durations where synchronous traffic is initiated and terminated These are conditions where access and fairness can become a reality. Alternative forms for handling synchronous traffic and for fairness control should be examined and compared and the best scheme from both an operational and performance standpoint implemented. Further, conditions where guaranteed access is required should be studied and documented. Load conditions should also simulate complex message traffic including broadcast and multi-cast, error handling for those messages whose addresses are corrupted, test of performance under software and hardware implemented acknowledge schemes and the study of the protocol's influence on upper level protocols, like TCP/IP. All of these investigations should be conducted over the wide range of network conditions which CSMA/RN is capable of handling.

Second, the controller logic should be built, tested and demonstrated so that its operations as noted in section 4 are better understood. While the first breadboard model can be built at a lower speed, later versions should built to handle gigabit rates. A computer logic simulation should accompany the hardware logic model so that tests for alternative and better logic procedures can be examined. This is especially true, if the controller logic is required to perform the fairness calculations within the nanosecond time frame that would be required in some forms of fairness control.

The implementation and integration of CSMA/RN into a frame/channel virtual circuit telephone system under both STM and ATM conditions requires further investigation in order to document both the performance and the hardware requirements for this form of operational CSMA/RN systems. The hardware integration should consider the basic controller logic, how it differs from that of the physical system and what systems can be used or modified within the present and future telephone systems to support implementation. In addition, it should consider the operational features of virtual CSMA/RN and how they differ from a physical implementation. An interesting feature of virtual circuit CSMA/RN is the possible load balancing trade offs between virtual circuit capacity and network load conditions so that the total system will perform at an ideal data rate based upon performance and resource cost. One could visualize that over a wide range of loads, using such a load balancing scheme, the system performance will be virtually constant and hence, extremely predicable by the user for both his asynchronous and synchronous data interchange operations. For ATM broadband ISDN systems, there is the additional possibility where CSMA/RN can provide a longer lasting connectivity service, i.e., a dedicated network based upon a lower level, normally more transient, packet-switched, asynchronous data service [17].

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